A Unified Operational Model of Spatial-Temporal Wave Confinement

A Traceable, Cross-Domain Framework Anchored in SI-Referenced Calibration and Public Geophysical Repositories

Carlos Daniel Borrego Romero, MBA, Bsc Computer Systems, CISA, CRISC, CDPSE, ISO 27001, CASE .NET

Independent Researcher — Pachuca Hidalgo, Mexico

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Scope and Intellectual-Property Notice

This preprint communicates the conceptual architecture, the observable-to-source mapping, the validation methodology, and the empirical coverage of the model. The operational core — the explicit field and window functional forms, the exact direct/spectral transform relations, the specific normalization and calibration rules, and the closed-form indicator definitions — is the subject of an intellectual-property filing (WIPO) and is deliberately withheld. The relations shown here are presented only at the level of named components, roles, and qualitative duality; they are insufficient, by design, to reconstruct, re-derive, reverse-engineer, or re-implement the protected formulation by analytical, numerical, or automated (including AI-assisted) means. Requests for evaluation under appropriate confidentiality arrangements may be directed to the author.

Companion note. *This model is the empirical observation-and-validation layer of the author's broader program — the Unified Variational Principle and the deterministic quantum-informational hash descriptor. Where those frameworks supply the unifying dynamics and the informational identity, the present model supplies a traceable bridge from formal wave structure to calibrated physical measurement.*

Abstract

We present the conceptual architecture of a **unified operational model of spatial-temporal wave confinement** — a single, domain-independent framework that describes how an oscillatory field is restricted in space and time to a finite or effective region, and that maps every observable consequence of that restriction onto variables retrievable from trusted, SI-referenced repositories. The model treats confinement as a structured modulation of a propagating field, with a complementary direct/spectral duality: localizing a field in the direct domain necessarily redistributes its content in the dual (wavenumber/frequency) domain. Rather than remaining a purely formal statement, each component is anchored to a real, measurable indicator — local amplitude, carrier frequency, wavefront and direction, spectral broadening, sidelobe structure, group delay, and dispersion — and to specific data sources, including NIST calibration and guided-wave electromagnetics[4][5], NASA Earthdata calibrated radiances[6], and NOAA NCEI marine geophysical archives[7]. The result is a reproducible, cross-platform evaluation scheme for electromagnetics, acoustics, and structural mechanics. This document states the architecture, the observable-to-source mapping, and the validation methodology, while withholding the operational core under intellectual-property protection.

1. Introduction

Spatial or temporal confinement of a wave appears throughout applied physics: finite apertures, apodization, beam steering, time gating, and radiation control. In each case the physical objective is the same — to limit the effective extent of a field within a useful region without destroying its local oscillation. Despite the ubiquity of the problem, treatments are typically domain-specific, and the link between the mathematical description of confinement and the calibrated quantities that one can actually measure is rarely made explicit.

This work addresses that gap with a single operational model that is *domain-independent* and *traceability-first*. Domain independence means the same architecture applies to electromagnetic, acoustic, and structural-

mechanical waves without structural change. Traceability-first means every component of the model is deliberately mapped to an observable indicator and to a trusted data source, so that the framework can be validated empirically rather than only asserted formally.

The contribution is therefore twofold: a unified description of confinement that exposes the direct/spectral trade-off common to all these domains, and an explicit, reproducible scheme connecting that description to SI-referenced metrology and public geophysical repositories.

2. The Confinement Architecture

At the highest level of description, the model represents the confined field as the result of applying a **confinement operation** to a propagating oscillatory field. The confinement operation is separable into a spatial part and a temporal part, each bounded between zero and one, so that the field is preserved where confinement is near-unity and suppressed elsewhere. Schematically:

$$\textit{confined field} \;\leftarrow\; (\textit{ propagating field }) \;\otimes\; [\textit{ spatial confinement} \cdot \textit{temporal confinement }]$$

The symbol $\otimes$ denotes the protected confinement operation; the bracketed entries are *roles*, not formulas. The explicit functional form of the field, of the confinement profiles, and of their composition is part of the protected core and is withheld.

2.1 The direct/spectral duality

The single most important structural consequence of the architecture is a **duality** between the direct domain and its dual. Restricting a field in space or time necessarily spreads its content in the conjugate variable — wavenumber or frequency. This is the qualitative, model-independent statement of the classical time–bandwidth and aperture–beamwidth trade-offs[1][2]. In the present framework it is elevated to an organizing principle: every benefit of confinement in one domain is paid for by a quantifiable cost in the dual domain.

$$\textit{localize in direct domain} \;\leftrightarrow\; \textit{redistribute in dual (wavenumber / frequency) domain}$$

Two qualitative consequences follow and are testable without the protected internals. Confinement that is sharper in space produces wider angular spreading and stronger sidelobe structure; confinement that is sharper in time produces wider spectral broadening and increased spectral leakage. These costs are precisely what the model's indicators are designed to quantify.

2.2 Component roles

The model is organized around a fixed set of physically meaningful components. Each is described here at the level of its role only.

- **Local field amplitude.** The slowly varying envelope and the magnitude of the field within the useful region.
- **Phase and delay.** The slowly varying phase, instantaneous phase, relative phase, and wavefront delay.
- **Carrier frequency and wavenumber.** The central temporal frequency and the principal spatial direction and wavenumber of propagation.
- **Spatial and temporal confinement profiles.** The applied aperture / mask in space and the activation / gating profile in time. Their exact forms are withheld.

- **Spectral responses.** The dual-domain signatures of the two confinement profiles — angular width and sidelobes in space, bandwidth and leakage in time.
- **Propagation descriptors.** Group velocity / group delay and dispersion, capturing how the confined packet is transported and broadened by the medium.

3. Observable-to-Source Mapping

The defining feature of the framework is that each component is bound to a measurable indicator and to a trusted, SI-referenced data source. The table summarizes this mapping at the level of observable and source only; it does not disclose any operational formula.

Model component	Measurable indicators	Trusted sources
Local field amplitude	RMS / peak amplitude, intensity, local energy	NIST Measurements & Calibrations; NIST dynamic mechanical metrology; NASA Earthdata radiometry [4][6]
Phase and delay	Instantaneous / relative phase, delay, wavefront	NIST frequency measurement & analysis; NOAA NCEI time-referenced geophysics [5][7]
Carrier frequency	Central frequency, linewidth, drift	NIST frequency analysis; NASA SMAP RFI / calibration [5][6]
Direction & wavenumber	Principal direction, angular pattern, wavenumber	NIST guided-wave electromagnetics; NOAA NCEI trackline geophysics [5][7]
Spatial confinement	Effective aperture, spatial transmittance, mask	Calibrated instrument specifications; NASA geolocation; NIST-traceable lab designs [4][6]
Temporal confinement	Activation time, duty cycle, ramps	NIST frequency & timing; NOAA / NASA time-stamped series [5][6][7]
Spectral responses	Angular width, sidelobes, bandwidth, leakage	NIST guided-wave EM; NASA SMAP calibration; NOAA NCEI geophysics [5][6][7]
Group velocity & dispersion	Group delay, packet transport, pulse broadening	NOAA NCEI time/position series; NIST SI-traceable benches; NASA geolocated products [4][6][7]

4. Coverage by Physical Domain

Empirical coverage is not uniform across domains; operational use must adapt to the real availability of calibrated data. The table summarizes coverage and the operational observation for each domain.

Domain	Primary sources	Coverage	Operational note
Electromagnetics	NIST guided-wave EM, NIST calibrations, NASA Earthdata radiometry [4][5][6]	High	Amplitude, frequency, geometry, RFI, spectral response
Acoustics	NIST dynamic mechanical metrology; microphone-sensitivity and acoustic standards [4]	High	Amplitude, phase, frequency, SNR, SI-traceable validation
Wave geophysics	NOAA NCEI marine trackline (MGD77T / MAG88T), seismic / sonar [7]	High	Time-and-position series, propagation, dispersion, spatial coverage

Domain	Primary sources	Coverage	Operational note
Structural mechanics	NIST vibration, acceleration, force; instrumented benches [4]	Medium	Strong calibration; breadth depends on experimental infrastructure

Globally, coverage is high for amplitude, frequency, time, energy, and temporal spectral response, and medium-to-high for direction, wavenumber, group velocity, and dispersion when dense space–time series are available.

5. Validation Methodology and Indicators

The precision of the scheme does not rest on a single variable. It rests on a one-to-one correspondence between each model component and a directly observable indicator, so that one can identify *which* part of the model explains each measured result. The indicator families are listed below at the level of what they quantify; their closed-form definitions are withheld.

- **Energy and amplitude indicators** — effective magnitude in the target region, transmitted energy, and the fraction of energy retained where confinement concentrates it (the energetic cost of confinement).
- **Spectral-fidelity indicators** — carrier-frequency shift and effective bandwidth (the frequency cost of temporal confinement).
- **Directional indicators** — main-lobe angular error, sidelobe level, and main-lobe width (the directional cost of spatial confinement).
- **Propagation indicators** — group delay and spectral curvature / pulse broadening (the medium's action on the envelope).
- **Global indicators** — target-region SNR and a normalized mean-square error summarizing agreement between prediction, simulation, and measurement.

A short, reproducible protocol governs use of the model: **(i)** select the physical domain and the primary trusted source; **(ii)** bind each model component to an observable variable in that source; **(iii)** verify spatial, temporal, spectral, and metrological coverage before fitting; **(iv)** compute per-component and then global precision indicators; and **(v)** normalize and compare against a reference or an unconfined baseline. The specific normalization rules are part of the protected core.

6. Limitations and Scope

The ideal confinement profile is a mathematical limit; in practice it is realized by apertures, masks, arrays, modulators, or material interfaces with finite resolution and additional losses. Therefore, even when data coverage is high, fit quality depends on instrumental fidelity, sampling density, and medium stability. In strongly nonlinear or dispersive media, the envelope description may require a higher-fidelity propagation model. The operational structure nonetheless remains useful as an observation, comparison, and validation layer, provided indicators are interpreted within their physical range of validity.

7. Discussion and Outlook

The model converts wave confinement from a domain-specific technique into a unified, traceable description in which every formal component is bound to a calibrated observable. Within the author's broader program, it provides the empirical observation-and-validation layer that complements the unifying dynamics of the Unified Variational Principle and the deterministic informational identity of the companion hash descriptor: it is the layer at which formal claims meet SI-referenced measurement.

Natural next steps are controlled disclosure of the operational core under confidentiality, reference implementations validated against the declared sources, and quantitative cross-domain studies of the confinement trade-offs in electromagnetic, acoustic, and geophysical data. Engagement is welcomed from the applied-physics, signal-processing, and metrology communities.

Intellectual-Property Statement

The conceptual architecture described in this document is original to the author. The operational core — the explicit field and window functional forms, the exact direct/spectral transform relations, the specific normalization and calibration rules, and the closed-form indicator definitions — is the subject of an intellectual-property filing (WIPO) and is withheld. Nothing in this preprint should be construed as a public disclosure sufficient to reconstruct, re-derive, reverse-engineer, or re-implement the protected formulation. The author retains all rights to the operational content.

References

[1] D. Gabor, "Theory of communication," J. Inst. Electr. Eng. 93 (III), 429 (1946) — time–frequency localization and the uncertainty trade-off. https://doi.org/10.1049/ji-3-2.1946.0074

[2] F. J. Harris, "On the use of windows for harmonic analysis with the discrete Fourier transform," Proc. IEEE 66 (1), 51 (1978) — windowing and spectral leakage. https://doi.org/10.1109/PROC.1978.10837

[3] B. D. Van Veen and K. M. Buckley, "Beamforming: a versatile approach to spatial filtering," IEEE ASSP Mag. 5 (2), 4 (1988) — aperture confinement and sidelobe structure. https://doi.org/10.1109/53.665

[4] National Institute of Standards and Technology, "Measurements and Calibrations" (PML) and "Calibration Services." https://www.nist.gov/calibrations

[5] National Institute of Standards and Technology, "Guided Wave Electromagnetics Group" (CTL RF Technology Division). https://www.nist.gov/ctl/rf-technology-division/guided-wave-electromagnetics-group

[6] NASA Earthdata, calibrated radiance and geolocation products (e.g., MODIS L1B, SMAP L1B RFI/Calibration). https://www.earthdata.nasa.gov/

[7] NOAA National Centers for Environmental Information (NCEI), Marine Trackline Geophysical Data (MGD77T / MAG88T). https://www.ngdc.noaa.gov/mgg/gdas/